Supernovae as sources of interstellar dust
星間ダストの供給源としての超新星

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1-1. Introduction

Supernovae are important sources of dust?

- Evolution of dust throughout the cosmic age
  - A large amount of dust (> $10^8 \text{M}_{\odot}$) in $z > 5$ quasars
  - Inventory of interstellar dust in our Galaxy

- Possible formation sites of dust
  - metal-rich ejecta of supernovae (Type II/ Ib/ Ic and Ia)
  - mass-loss winds of AGB stars
  - grain growth in the ISM (molecular clouds)
  - mass-loss winds of massive (RG and WR) stars, novae, quasar outflow ...
1-2. Mass and size of dust ejected from SN II-P


**Total dust mass surviving the destruction in Type II-P SNRs:**
0.07-0.8 M$_{\text{sun}}$ ($n_{H,0}$ = 0.1-1 cm$^{-3}$)

**Size distribution of surviving dust is dominated by large grains (> 0.01 µm)**
2-1. Dust formation in Type IIb SN

**SN IIb model** (SN1993J-like model)

- $M_{\text{ej}} = 2.94 \ M_{\odot}$
- $M_{\text{ZAMS}} = 18 \ M_{\odot}$
- $M_{\text{H-env}} = 0.08 \ M_{\odot}$
- $E_{51} = 1$
- $M(^{56}\text{Ni}) = 0.07 \ M_{\odot}$

![Diagrams showing temperature, density, and velocity profiles](image)
2-2. Dependence of dust radii on SN type

- condensation time of dust
  300-700 d after explosion

- total mass of dust formed
  • 0.167 $M_{\odot}$ in SN IIb
  • 0.1-1 $M_{\odot}$ in SN II-P

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- the radius of dust formed in H-stripped SNe is small
  - SN IIb without massive H-env $\Rightarrow a_{\text{dust}} < 0.01 \mu m$
  - SN II-P with massive H-env $\Rightarrow a_{\text{dust}} > 0.01 \mu m$
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of $n_H > 0.1 / \text{cc}$

$\Rightarrow$ small radius of newly formed dust

$\Rightarrow$ early arrival of reverse shock at dust-forming region

2-4. IR emission from dust in Cassiopeia A SNR


- **total mass of dust formed**
  \[ M_{dust} = 0.167 \, M_{\text{sun}} \]
- **shocked dust**
  \[ M_{d,\text{warm}} = 0.008 \, M_{\text{sun}} \]
- **unshocked dust**
  \[ M_{d,\text{cool}} = 0.072 \, M_{\text{sun}} \]
  with \( T_{dust} \sim 40 \, K \)

**AKARI observation**
- \( M_{d,\text{cool}} = 0.03-0.06 \, M_{\text{sun}} \)
- \( T_{dust} = 33-41 \, K \) (Sibthorpe+10)

**Herschel observation**
- \( M_{d,\text{cool}} = 0.075 \, M_{\text{sun}} \)
- \( T_{dust} \sim 35 \, K \) (Barlow+10)
3-1. Difference in estimate of dust mass in SNe

**Theoretical studies**

- at time of dust formation: \( M_{\text{dust}} = 0.1 \text{-} 1 \, M_{\odot} \) in CCSNe
  (Nozawa+03; Todini & Ferrara 01; Cherchneff & Dwek 10)

- after destruction of dust by reverse shock (SNe II-P):
  \( M_{\text{surv}} \sim 0.01 \text{-} 0.8 \, M_{\odot} \) (Nozawa+07; Bianchi & Schneider 07)

  Dust amount needed to explain massive dust at high-z

**Observational works**

- MIR observations of SNe: \( M_{\text{dust}} < 10^{-3} \, M_{\odot} \)
  (e.g., Ercolano+07; Sakon+09; Kotak+09)

- submm observations of SNRs: \( M_{\text{dust}} > 1 \, M_{\odot} \)
  (Dunne+03; Morgan+03; Dunne+09; Krause+05)

- MIR/FIR observation of Cas A: \( M_{\text{dust}} = 0.02 \text{-} 0.075 \, M_{\odot} \)
  (Rho+08; Sibthorpe+09; Barlow+10)
3-2. Missing-dust problem in CCSNe

Tanaka, TN, +11, submitted

Young supernovae: Ercolano+07, Wooden+93, Dwek+92, Pozzo+04, Elmhamdi+03, Meikle+07, Szalai+10, Kotak+09, Mattila+08, Sakon+09

Supernova remnants: Rho+08, Sibthorpe+10, Barlow+10, Nozawa+10, Morton+07, Green+04, Temim+06, Rho+09, Sandstrom+09, Williams+08, Temim+10

Optically thick??

$\tau \propto \rho r \propto t^{-2}$
3-3. Detectability of SNe-dust with SPICA

Tanaka, TN, +11, submitted

Massive dust can be hidden if $T_{\text{dust}} < 100$ K
3-4. Detectability of cold dust with ALMA

**SN1987A**

- **MIR image**
  - SN 1987A in LMC
diameter: 2", most feasible

- 1E0102.2-7219 in SMC
diameter: 40"
too extended to be detected
  ➔ integration time: ~100 day

 integral time: ~100 day

- **ALMA**
  - $T_{dust}=20$ K
  - $M_{dust}=0.1 M_\odot$
  - $a_{dust}=0.1 \mu m$

- **SN1987A**
  - Cas A @60kpc
  - $M_{d, warm}=0.008$ M$_\odot$
  - $M_{d, cool}=0.072$ M$_\odot$

with $T_{dust}=43$ K

- **SPICA LRS(10m)**
- **ALMA (1h)**

**Graphs**

- Flux, $F_\nu (mJy)$ vs. Wavelength ($\mu m$)
- Logarithmic scales for flux and wavelength.
4-1. Dust formation in Type Ia SN

Type Ia SN model

W7 model (C-deflagration) (Nomoto+84; Thielemann+86)

- $M_{\text{ej}} = 1.38 \, M_{\odot}$
- $E_{51} = 1.3$
- $M(^{56}\text{Ni}) = 0.6 \, M_{\odot}$

![Graph showing number abundance and gas velocity over enclosed mass and normalized enclosed mass](image)
4-2. Dust formation and evolution in SNe Ia

- condensation time: 100-300 days
- average radius of dust: $a_{\text{ave}} \sim 0.01 \ \mu m$
- total dust mass: $M_{\text{dust}} = 0.1-0.2 \ M_{\odot}$

⇒ SNe Ia are unlikely to be major sources of dust

Nozawa+11, submitted
dust destruction in SNRs

newly formed grains are completely destroyed for ISM density of $n_H > 0.1 \ \text{cm}^{-3}$
5. Summary of this talk

- Size of newly formed dust depends on types of SNe
  - H-retaining SNe (Type II-P) : $a_{\text{ave}} > 0.01 \ \mu\text{m}$
  - H-stripped SNe (Type IIb/Ib/Ic and Ia) : $a_{\text{ave}} < 0.01 \ \mu\text{m}$
  ⇒ dust is almost completely destroyed in the SNRs
  ⇒ H-stripped SNe may be poor producers of dust

- Our model treating dust formation and evolution self-consistently can reproduce IR emission from Cas A

- Mass of dust in SNe must be dominated by cool dust
  - FIR and submm observations of SNe are essential
  - SPICA will make great advances on understanding of dust formation process in SNe